Towards the Adoption of Automated Regulatory Compliance Checking in the Built Environment

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Abstract

Automated compliance checking brings advantages to the built environment but, currently, there has been no meaningful adoption, despite the increasing maturity of asset information models.

This paper addresses this by ascertaining the blockers/obstacles to adoption and develops a road-map to overcome them. This work has been conducted in the UK and a road-map has been produced to drive forward adoption. More specifically this paper has; assessed the current state of the art in the field and engaged with industry to examine the attitudes to the digitisation of regulatory compliance processes

The results showed that industry believes that adoption of automation was both feasible and desirable, with the caveat that human oversight be maintained.

Our road-map's methodical list of steps was judged to have the potential to bring the construction industry to the verge of mass industrialisation of automated compliance checking by 2025.

Keywords: Automated Regulatory Compliance Building Information Modelling Compliance Checking Building Performance

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1. Introduction

The entire lifecycle of the built environment is governed by a variety of regulations, requirements and standards[1] . These range from contractual requirements, requirements specified in the project brief, legislation, and self-imposed environmental performance recommendations. The checking of compliance against these is a complex task that is currently performed on a manual basis thus is highly resource intensive [2].

So far there has been no adoption of automated compliance checking as part of official compliance processes. The one exception to this is Singapore[3], who implemented an automated system, but this has now been discontinued.

The historical reason behind this lack of adoption is because data-sets created during planning stages were not sufficiently mature[2]. However, the increasing maturity of Asset Information Models (AIM) and the adoption of Building Information Modelling (BIM) mean automation of compliance checking is becoming feasible. In this context an AIM is defined as the collated sources of data and information required for the ongoing management of an asset [4]. Additionally, BIM refers to the process of creating and managing information about a construction project across it's life-cycle [5].

It is anticipated that this concept of automated checking can bring tangible advantages including increased efficiency and a reduction in costs [2, 6, 7].

The current state of the art in this field includes limited software vendor adoption of compliance processes together with scattered development of ad-hoc approaches for monitoring/achieving compliance against regulations/requirements across varying stages of the construction life-cycle [1]. These ad-hoc solutions lack scalability, transferability from one building to another, and accessibility for non expert users.

This is demonstrated by the fact that continual assessment (the process of repeatedly, over a given time window, checking an assets compliance against a regulation) of a building's compliance against requirements is rarely seen in practice in operational buildings, illustrating a lack of systematic management of built assets [8]. This is indicative of the wider problem of compliance processes being weak and complex with poor record keeping and change control [9], demonstrating the key need for further research in this area.

Previous work in this area includes significant existing reviews of academic literature and current software implementations [6, 7, 10, 11, 12, 13]. However, these works primarily focus on the technical challenges, and, thus, do not consider challenges across a technical, commercial and political spectrum. This paper will fill this research gap by understanding the multi-faceted obstacles that have prevented the adoption of the automated regulatory compliance checking and propose a road-map to overcome these obstacles.

This paper will do this in two steps; **(a)** ascertain the political,technical and commercial blockers/obstacles that are preventing the widespread adoption of the digitisation of regulatory compliance in the built environment and **(b)** formulate a road-map together with industry traction to overcome these blockers and drive forward adoption of automated checking processes across both academic and industrial contexts.

To achieve this, this paper utilises a generic methodology that will; (a) assess the current state of the art in this field, including both academic work and industrial tools, (b) ascertain current attitudes to the digitisation of regulatory compliance from the UK construction industry, (c) consult with industrial stakeholders to elicit the political, commercial and technical obstacles to further adoption of automated compliance processes.

Once developed, it is our view that this road-map can achieve a transformation of the regulatory compliance system, offering a comprehensive and methodical list of next steps over the next several years, bringing the construction industry to the verge of mass adoption of automated compliance checking.

In the remainder of this paper, Section 2 will present the methodology and vision of this paper. Section 3 will then present the results of the landscape research into industry and academic developments, Section 4 will present the survey conducted to ascertain the views of the industry. Section 5 will present the results of the consultation exercise and the final research road-map. Section

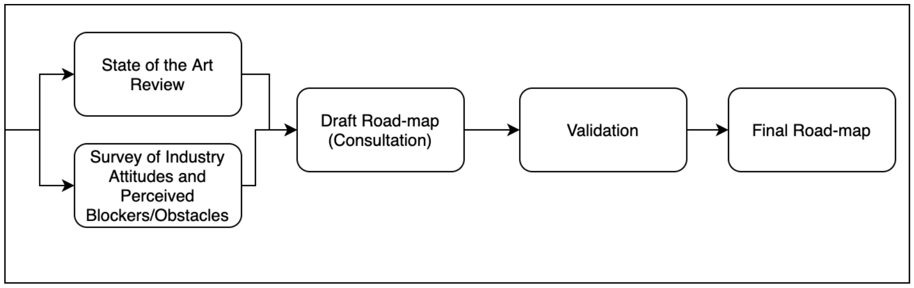

Figure 1: Methodology

6 will document the validation of the road-map. Finally, section 7 will conclude the paper.

2. Methodology

The section will present the methodological framing of this work. This paper attempts to answer to key research questions;

1. Why has automated regulatory compliance not yet achieved widespread adoption in the built environment domain?
2. What is a viable route towards adoption for automated regulatory compliance?

To solve these questions, a positivist philosophical stance [14] is adopted, involving a quantitative and qualitative approach as illustrated in Figure 1.

More specifically, this methodology consists of the following steps, which will draw on both primary and secondary sources of evidence (literature and industry participation).

1. Conduct a detailed landscape review of applicable industrial and academic developments.
2. Survey (n=60) the industry to ascertain the industry views on:
    - The adoption of automated compliance checking.

    - The current obstacles or blockers to the adoption of automated compliance checking and the industry capabilities required to overcome them.

3. Formalise the results into a road-map through a consultation involving 19 industry experts.
4. Validate the road-map through further interviews with 6 further significant industry figures.

The scope of this work has been set deliberately wide, to incorporate all aspects of regulatory compliance activity. This scope considers:

- Different types of built environment assets from buildings, to districts, to infrastructure.
- The entire life cycle of these assets from brief and design through to operation and refurbishment/retrofitting.
- The context on which checking systems are operating:
    1. Advisory: Where checking systems are used to inform the brief/design processes.
    2. Creative: Where checking systems are used as an integrated part of design processes.
    3. Decisive: Where checking systems are used to decide whether or not compliance is achieved.
- The different users that will utilise compliance systems in different ways.
- The type of check that compliance systems are performing:
    1. Regulations; Rules or directive made by an authority i.e. compliance with legislation.
    2. Requirements: Necessary conditions i.e. compliance with requirements set as part of a project brief.

3. Recommendations: A suggestion or a proposal, often, but not always put forward by an authority, but to which compliance is not mandatory.

- The varying degrees of automation offered by checking systems, i.e. from preparatory systems (that simply prepare information for checking) to fully automated checking systems.

3. Landscape Review

This section will present a summary of the current research landscape, together with an analysis of existing tools available in this field.

3.1. Landscape Review of Current Research

This section will briefly review the research landscape in the field of automated regulatory compliance.

The first work in this field was conducted by Fenves[15], who studied the representation of structural design requirements using tabular decision logic. Then, in 1997 Han et al. anticipated the need for automated code checking with a proof-of-concept prototype allowing explicit specification of functional requirements and design parameters [16].

Then next significant piece of work was in 2006. Here DesignCheck, a tool for automated code checking, was presented [17]. DesignCheck uses Industry Foundation Classes (IFC) models as a bridge between its internal model and third-party Computer-Aided Design (CAD) tools.

Then, in a 2009 survey, Eastman et al. pointed out the shortcomings of existing rule-based checking systems [6],in terms of rule writing (particularly for a non programming expert), rule digitisation, rule base management and tool integration. From their review, these authors extrapolated general requirements for rule checking system development: a method to translate natural language statements into logic-based statements and a method to semantically enrich the design model with objects and relations required by the obtained rules. They created their algorithm following an iterative method that combines classification of building codes, analysis of codes for automated checking, extraction of requirements for fire resistance, evacuation stairways and fire protection partitions, extraction of relevant information from the BIM model, evaluation of missing information, algorithm refinement and benchmarking against the same checking performed manually.

In 2010, Greenwood et al. inferred guidelines for future BIM-based compliance checking by reviewing existing implementations of code compliance checking [7]. They extracted the following guidelines: (a) machine interpretable rules should be understandable by regulation authors; (b) rule bases should be CAD implementation-neutral (this is key for localisation of checking systems); (c) consequently open standards should be favoured; and, (d) model checking should be integrated with the model authoring processes, to ensure applicability of the checking rules. Also in 2010, Tan et al. proposed an approach to combine results from the hygrothermal performance simulation of a building envelope with building codes to support compliance checking [18].

In 2011, Salama and El-Gohary proposed an approach to enrich the knowledge representation and reasoning of underlying compliance checking rules beyond commonly-used if-then-else rules [19]. Also in 2011, Zhang et al. implemented an automated object-oriented rule checker with a view to integrate safety planning in the design process for better project execution planning [20].

There was an increase in activity in 2013. Firstly Dimyadi and Amor again assessed the state of automated code compliance checking [11, 10]. Their review highlighted that the availability of both digital representations of building objects and computable representations of regulation texts, as being the main challenge of automated compliance checking.

Subsequently, Hjelseth also proposed a methodology to facilitate the integration of regulation texts in BIM-based code checking tools [21]. His methodology relies on three main procedures: “transcribe” (those rules that are computable), “transfer” (those that are not computable) and “transform” (those that can be transformed to be computable). Also in 2013, Melzner et al. performed a case study of BIM-based automated compliance checking, using decision tables, for early detection of fall hazards as part of the safety planning workflow [22]. The LicA tool was also proposed in 2013 by Martins et al. This is a tool that automatically assesses the compliance of a building's water network design with a subset of the Portuguese domestic water systems regulations [23]. Finally, Salama and El-Gohary [24] presented an implementation of an information extraction tool supported by both semantic modelling and machine learning. These authors used rigorously tuned Support Vector Machine algorithms to classify the clauses of general conditions of construction contracts according to the concepts of the deontic model.

In 2014, Cheng and Das presented their web service based framework for green building code checking and simulation [25]. Their approach, which utilises a rule engine and is based on Green Building XML (gbXML) models, evaluates and updates models iteratively by requesting input from multi-location cross-organisational collaborators.

In 2015, Lee et al. applied automated rule-based checking to accessibility and visibility [26]. Their approach is based on Lee's BERA language. BERA is a domain specific programming language, to define, analyse and check rules [27]. Also in 2015, Ciribini et al. presented an innovative use of model checking with a BIM-based e-procurement framework [28]. Their research methodology consisted in converting an existing set of tendering texts into computable rules using Solibri Model Checker (following the RASE methodology) and of tendering drawings into a BIM model using Revit. Macit et al. also presented a hybrid model to represent building code using both the four-level paradigm and semantic modelling [29]. The four levels derive from the semantic modelling approach of SMARTcodes, they are: the domain level, the rule level, the ruleset level and the management level. Hjelseth also proposed a classification of BIM-based model checking into four categories [12]: validating (i.e. checking the compliance to some requirement/regulation), guidance (i.e. proposing solutions with respect to best practices), adaptive (i.e. automatically adjust a building object to conform to the rules) and content (i.e. examining the completeness of a BIM model against a specific use). Zhang & El-Gohary[30] used rule-based semantic natural language processing techniques to automate the extraction and the machine-process-able representation of regulatory requirements from textual regulatory documents. Their method was tested on a number of clauses from the International Building Code and evaluated by comparison with a manually generated reference. These authors were then able to identify sources of errors, that would allow to improve the automated.

Finally, in 2015, RegBIM [2] was developed as an end to end methodology for regulatory compliance, underpinned by the use of IFCs as a data model. The methodology behind the software includes; (a) the use of regulation experts to mark up regulatory documents using RASE [31], (b) the use of BIM experts to map between the regulations and IFC data models, (c) the use of a rule engine (later a semantic model) to perform the compliance checking, and (d) an innovative user interface to show the complex structure of compliance checking results to end users in an easily understood way.

In 2016, Krijnen et al. published an overview of technologies for requirement checking on building models [13]. According to these authors, automated rule checking requires a holistic integration between classification systems, concept libraries, query languages, reasoners and model view definitions. Also in 2016 Zhang et al. developed algorithms for BIM-based automated safety checking [32], using a rule-based NLP method to extract information from construction regulatory documents [33]. Zhang et al[34] also presented an NLP-based methodology to semi-automate the generation of BIM extensions to support automated compliance checking. The methodology combined: (a) part-of-speech pattern matching to extract regulatory concepts, (b) term-based matching and semantic-based matching to select relevant IFC concepts and machine-learning based classification to identify relationships between pairs of concepts.

In 2017, Hakim et al. proposed a classification system for automated compliance checking rules to support their translation from plain language to computable language [35]. The classification consists in three main categories, according to the quantity and complexity of BIM data required by the rule, each category being subdivided into two sub-classes according to the level of compliance with IFC. Also in 2017, Dimiyadi et al [36] evaluated the adequacy of LegalDocML and LegalRuleML to support automated compliance checking in the AEC and FM domains.

In 2018, Zhong et al. designed an ontology-based framework for building environmental monitoring and compliance checking [37]. The framework is built upon a BIM ontology (derived from IFCOWL), a sensor ontology (W3C's SSN ontology) and an ontology of building regulations. SPARQL Protocol and RDF Query Language (SPARQL) queries are used to formalise the rules and constrains from building regulations. Also in 2018, Jiang et al. proposed a semi-automated green building evaluation framework based on an ontology that enriches BIM models with the required multidisciplinary data (GBEOntology) [38]. Their framework consists of a text knowledge extraction process, a BIM information extraction process, and a ontology building and reasoning process (combining SWRL rules and the JESS rule engine).Zhang & El-Gohary[39] also proposed an approach to differentiate and assess the computability of code requirements and sentences to inform NLP-based automated compliance checking methods. Their approach: (a) pre-processed a corpus of natural language code requirements, (b) performed clustering analysis of the pre-processed corpus, (c) characterised each cluster in terms of semantic and syntactic structure, and assessing the computability of cluster elements. Applying the approach to a portion of the International Building Code, the authors identified classes of code sentences that are particularly challenging to represent computationally.

In 2019, Nawari[40, 41] define a conceptual and theoretical framework to standardise the extraction of regulatory requirements from textual regulations for design review and propose a modular architecture for the implementation of automated design review. The framework classifies regulation clauses into four categories: content (definitions), provisory (explicit rules), dependent (on provisory clauses) and ambiguous (fuzzy knowledge). The formal language proposed by the paper is based on an object-driven representation of rules that can deal with uncertainty. The framework is flexible and can adapt to various engineering design disciplines. This work specifically focuses on checking of compliance against IFC models.

Bus et al.[42] experimented with an approach based on semantic web technologies for compliance checking, using the IfcOWL ontology. Their approach consisted of: (a) homogenising the modelling style among different stakeholders of a project using a reference BIM Execution Plan, (b) creating regulatory terminology by enriching the IfcOWL vocabulary with explicit and inferred regulatory concepts, (c) simplifying the semantic representation of geometrical features by computing IFC object bounding boxes, (d) and generating machine-processable regulatory requirements by semi-automatically converting natural language rules into SPARQL queries. They tested this approach with French fire safety and accessibility regulations. Finally, Zhang [43] focused on the possibility of using current open standards for capturing requirements in the building industry to automatically check building models. Based on this an approach was developed together with the ability to query related semantic and geometric information in building models. A research prototype was constructed and this approach was validated.

Nawari et al[44], proposed the Generalized Adaptive Framework (GAF). GAF is a process for computerizing regulatory compliance checking based on a object-based representation of building regulations. It enables the translation of regulations into efficient computable expressions.

Using the GAF approach, [45] presented the development of a virtual permitting process for the state of Florida. Based on an analysis with local stakeholders a virtual permitting framework is proposed using building information modelling is proposed. This computable model generate using the GAF approach is then linked with a building information model using model view definitions. This work was subsequently further expanded and deployed in the post disaster recovery use case [46].

A summary of the papers reviewed in this section that resulted in tangible demonstrable prototypes are summarised in Table 1. It should be noted that the "Allows for Digitisation" column refers to the ability of the work to facilitate the digitisation of new regulations in some convenient way (i.e. excluding manual coding or modelling).

Table 1: Academic Research Summary

Name	Subject of compliance checking	Allows for Digitisations	Checking Methodology	Input Data Format	Output Data Format
Singapore CORENET e-PlanCheck[3]	Regulations from Singapore related to building design, fire safety, water, energy usage, barrier-free access	No	Submission of Building Model to Server	IFC building models enriched with calculations made with FORNAX engine	Compliance report displayed in 3D view of CORENET web interface
DesignCheck [16]	Disabled access regulations	No	Checking against single IFC Model	IFC models enriched with code-related properties	Interactive report page and print- friendly report page
Tan[18]	Building Envelope Design	No	Single Model Check	Expanded Object Model	Report
Zhang [20]	Site Safety	No	Single Model Checking in Tekla	Tekla API	Report
Melzner[22]	Site Safety	No	Single Model Check	IFC	Report

LiCA[23]	Water Distribution Systems	No	Single Model Checked(via a process of conversion)	IFC	Report and Visualisation
Cheng and Das[25]	Energy Simulation	No	Single Model Check	GBXML	Report
Lee[26]	NA	Yes - Domain Specific Language	Single Model Check	IFC	Report
Ciribini[28]	Tenders	Yes - Rase	Single Revit Model	Revit	Report
Macit[29]	İzmir Municipality Housing and Zoning Code	No	Single Model	Not specific	Not specified
RegBIM[2]	UK Building Regulations	Yes - RASE	Submission of single model	IFC	IFC + JSON Report
Zhang[33]	International Building Code	Yes - via NLP	Sinle Model	IFC	Report
Dimiyadi[36]	New Zealand Building Code	Using LegalRuleML	Single Model	IFCOwl	Report
Zhong[37]	Environmental Monitoring	No	Single Model Checking	IFCOwl	Report

Zhang and El-Gohary[39]	2015 International Building Code	Presents a methodology for identifying the different types of building code requirements in terms of computability and if they can be automated	NA	NA	NA
Nawari[40]	Florida Building Code	Yes, proposes a framework for automating code compliance	Single Model Checking	IFCXml	Report
Nawari[44]	Construction Regulations	Generalised Adaptive Framework - A framework to convert regulations into computable models	NA	IFC	NA
Messaoudi[45, 46]	Permitting for State of Florida	No	Single Model Submission	IFC	Report

Bus[42]	French Fire Safety, Accessibility Regulations	No	Single Model Submission	IFCOwl	Report
Zhang[43]	Multiple Use Cases (Norway, US, South Korea)	No	Single Model File	IFCOwl	BCF

3.2. Existing Industrial/Academic Tools

This subsection summarises the currently available tools offering regulatory compliance functionality. This analysis was performed by identifying, in collaboration with industry, the tools currently available. Each tool deemed to be in scope for this study was then analysed, where a license was not available academically, the assistance of an industry partner was sought to aid in analysing the software.

This is summarised in Table 2.

Table 2: Existing Industry Tools

Name	Subject of compliance checking	Allows for Digitisations	Checking Methodology	Input Data Format	Output Data Format	Status
AEC3 Require1	No inbuilt regulations	Yes any regulation - using markup	User performs an automated check of design model against all digitised standards	IFC	Textual Reports, XML and IFC	Pre-Commercial

Autodesk Model Checker	Multiple rulesets available	Manual specification or customization of rulesets	User performs an automated check of design model against selected rulesets	Revit	Report	Commercial
BriefBuilder	Client Requirements	GUI requirement capture at building room level	Checks rooms or buildings against attached regulations	IFC+Revit	Report	Commercial
CARS	Design Manual for Roads and Bridges	Specified via a structured word processing tool	No checking but rules access via an API	NA	NA	Not Public
GliderBIM	Custom Rulesets	GUI-based validation ruleset editor	Automated model validation against rulesets	IFC	Reports or RFIs	Commercial

Xinaps	Rules for a variety of local accessibility and fire safety standards/regulations	No	Checking of entire model against predefined regulations	Revit	Visual Analysis	Commercial
UpCodes AI	Rules for a variety of US state building codes	No	Run code check on entire current Revit model	Revit	Reports	Pre-Commercial
SMART review	Predefined checking rules for the International Building Code	No	Allows architects to check compliance of entire building design	Produces detailed textual checking review in navigable HTML	Revit	Commercial
Jotne EDMmodelchecker	None	Define rules and constraints as an EXPRESS schema	Selected Rules on entire model	IFC	Violations from constraints visualised in a HTML format	Previously Commercial

Solibri Site or Enterprise Versions	Many sample rulesets including accessibility and intersections	Generic Rule Templates customized using the GUI-based Ruleset Manager	Selected Rules on entire model	IFC	Report based	Commercial

3.3. Conclusion

This section has reviewed both the state of the art research and current industry tools in the area of automating regulatory compliance in the built environment.

This has presented three key findings; (a) that there is a large quantity of high quality/research tools in this area, all adopting a variety of technologies/methodologies, (b) despite this, there are only 6 commercial tools available in this area, (c) there is currently no mainstream adoption of automated compliance checking tools as part of official compliance processes. This is in spite of the huge drive for digitisation currently underway in many countries.

This demonstrates, by the relatively few commercial solutions, that there are significant obstacles to achieving a viable commercial product in this space. Examining the variety of technological solutions that have been successfully developed but not yet commercialised also leads to the conclusion that the primary obstacles is not a lack of viable technological approaches, but instead more commercial, political and standardisation concerns.

More specifically, the analysis of the literature allows the elicitation of a set of twelve initial obstacles:

1. Lack of shared open standards for regulation clauses. In literature there are many suggested approaches to representing regulations including the IFCs and various logical languages [44, 26, 2, 47] , however, there is yet

to be a consensus reached as to the best approach upon which a standard can be built.

2. Lack of artificial intelligence technologies to interpret between regulations/requirements and proposals, such as natural language processing.
3. Lack of existing rule processes to track decisions and uncertainty. Work has been done to deal with uncertainty of data, [44] , however there is still further research needed to fully deal with the uncertainty and changing requirements commonly found in the early stages of construction projects.
4. Inability of brief and regulatory requirements to be contractually enforceable.
5. Lack of requirements stipulating use of as proposed/designed and as built structured asset information (e.g. BIM) for non-domestic projects.
6. Lack of requirements stipulating use of proposed/designed and as built structured asset information (e.g. BIM) for all projects.
7. Lack of established primacy of structured asset information (e.g. BIM) over documentation and drawings for the purposes of compliance submission.
8. Lack of defined strict legal responsibility for compliance.
9. No ability or right for general public to see compliance assessments.
10. Lack of standard data and criteria for social, environment and economic impact assessments.
11. No business models developed for reduced costs for automated assessment.
12. No current tool able to offer complete ability to pre-check for compliance prior to formal submission. While Table 1 lists multiple approaches that offer the ability to check against design time models, none, with the exception of [3], have achieved industry level adoption

Specifically, in relation to items 5-7, while academic literature is strongly in favour of BIM adoption, the wider industry has not yet reached a state of where BIM data has achieved primacy in all projects [48].

Thus, this review has provided important indications as to the type of obstacles present in the adoption of automated regulatory compliance. These obstacles will now be explored in more detail and in the following sections.

4. Survey of Industry Attitudes to Automated Compliance Checking

This section will document the survey conducted by this work. This survey was designed to fulfil two goals; (a) to test industry attitudes with regards to the acceptance of the automated compliance checking and (b) to elicit a set of initial obstacles to the adoption of automated regulatory compliance.

The survey was distributed widely through industry networks, social media and individual contacts of our industry partners. The survey was distributed directly to a total of 215 individuals, however the snowball effect and social media dissemination may well mean more people received the survey. A total of 60 respondents completed the survey (all received responses were valid), a significant response for a specialised detailed survey, that required significant effort to complete.

The questionnaire was targeted at industry professionals, with experience in either assessing regulatory compliance, defining regulations or having their work checked against regulations. Thus it required detailed responses to some questions, possibly explaining the lower response rate. It consisted of a mix of open and closed questions to allow quantitative data to be collected regarding the state of the nation, but still allowed respondents to express their views.

The primary questions were designed to measure industry attitudes to the digitisation of compliance checking. The questions asked respondents what level of automated checking they thought was possible by 2025. Respondents were asked to rate this from three viewpoints; technological, commercial and political. They were asked to rate automation on the following scale:

- 0 - No Automation: The current document and drawing based procedures are adequate

- 1 - Automated Information Exchange: Automating submission of project information for regulatory compliance
- 2 - Automated Validation: Automating the checking of information for completeness prior to compliance checking.
- 3 - Partial Automated Assessment: Automatic assessment of some key regulations.
- 4 – Automated Assessment: Fully Automated assessment but requiring final human approval.
- 5 - Full Automation: Fully automated compliance checking.

In addition to these closed questions, respondents were also provided with free text questions to add their own views.

To understand the key obstacles to achieving automated regulatory compliance, respondents were asked to rate the obstacles elicited previously in Section 3. Respondents were asked to rate these on a scale of how desirable a solution to this obstacle is (on a scale of 1-4, where 1 is not required, 2 desirable, 3 highly desirable and 4 is essential). In addition, respondents were also given the ability to add their own suggestions.

Table 3 describes the level of automation deemed achievable by the respondents.

Overwhelmingly Table 3 shows that respondents indicated that automation was possible, with the vast majority of respondents believing some level (partial of automation with human oversight) is achievable by 2025. These responses have shown us that there is a definite appetite within the industry for automation and that this automation is achievable by 2025. However, as a cautionary note, the responses were very clear that full automation (without human intervention) is not desirable, nor possible within this timescale.

Table 4 shows the average rating of each of the obstacles suggested by the survey. It should be noted that the distinction between domestic and non-domestic

Rating	Technology (%)	Political (%)	Commercial (%)
0 - No Automation	0%	3.3%	1.7%
1 - Automated Information Exchange	0%	11.7%	5.0%
2 - Automated Validation	8.3%	8.3%	13.3%
3 - Partial Automated Assessment	40%	21.7%	43.3%
4 – Automated Assessment	40%	36.7%	30%
5 - Full Automation	17%	18.3%	6.7%

Table 3: Level of Automation Achievable

projects has been made due to the often different regulatory requirements of these different building types

In addition to these ratings nearly every respondent provided free text suggestions for additional obstacles. These have been analysed and listed below, the number in brackets signifies how many respondents suggested this obstacle:

- Lack of precise digitisable regulations (21).
- Lack of standardised data models for regulatory compliance data (18).
- Lack of clear government direction towards automated compliance checking and engagement with appropriate government departments (12).
- Cultural resistance to accepting automated compliance checking (7).
- Lack of investment in automated compliance checking (5).
- Lack of technology/tools to support checking as-built assets (4).
- No business models factoring in: (a) reduced costs for assessment, (b) faster turnaround for assessment and (c) ability to pre-check prior to formal submission (4).
- Lack of awareness of the meaning automation of regulations, requirements and standards and its benefits (4).

Capability	Mean Score
Lack of shared open standards for regulation clauses	3.85
No current tools able to offer complete ability to pre-check for compliance prior to formal submission	3.46
Inability of brief and regulatory requirements to be contractually enforceable	3.45
Lack of existing rule processes to track decisions and uncertainty.	3.36
Lack of defined strict legal responsibility for compliance	3.33
Lack of requirements stipulating use of as proposed/designed and as built structured asset information (e.g. BIM) for non-domestic projects	3.26
Lack of established primacy of structured asset information (e.g. BIM) over documentation and drawings for the purposes of compliance submission	3.21
Lack of requirements stipulating use of proposed/designed and as built structured asset information (e.g. BIM) for all projects	2.85
Lack of Standard data and criteria for social, environment and economic impact assessments	2.83
No model for reduced costs for automated assessment	2.71
Lack of artificial intelligence technologies to interpret between regulations/requirements and proposals, such as natural language processing	2.68
No public rights to see compliance assessments	2.38

Table 4: Obstacle Ratings

- Lack of generative design tools based on regulations/requirements (3).
- Lack of implementation of smart contracts (3).
- Lack of standardised APIs for compliance checking tools (3).
- Insufficient professional development and training in compliance checking (3).
- Poor compliance checking process definition, standardisation and management (2).
- Lack of explicit linkages between requirements, designers and product suppliers and their data (2).
- No services to enable certification of software as performing "correct" checking (2).
- Poor structured product data standards (2).
- Existing of negotiated regulations decreasing the transparency of regulations (2).
- Lack of a formal data "Chain of custody" (1).
- Lack of dual automated and engineered paths to ease transition (1).

This section has reported on the results of the survey conducted. This has identified that the industry attitudes are favourable to the adoption of automated compliance checking, subject to the caveat that final human approval is maintained. Furthermore, a set of obstacles have been identified, rated and expanded upon by respondents. These obstacles will form the starting point for developing a road-map towards achieving automated regulatory compliance. This process will be discussed in the following section.

5. Developing a Road-map and Vision for the Future of Digitised Regulatory Compliance

This section describes the development of the vision and road-map for the future of automated compliance checking. The road-map and vision are linked - the vision shows the final view on what the future of automated of compliance checking will look like, the road-map is the detailed steps required to achieve it.

The development of the road-map and vision was delivered via an industry consultation event. The participants of this were drawn from survey respondents (an open invitation was issued to all who participated and gave contact details).Nineteen industry experts participated in this consultation event. These included representations from the following types of organisations:

- Academia
- Industry Research Organisations
- Architectural Practices
- Contractors
- Highways Agencies
- Health and Safety Organisations
- Facilities Management
- Certification Bodies.

In advance of the event, a list, with explanations, of the obstacles elicited from the survey was distributed to attendees.

At the consultation event itself, firstly the initial set of obstacles were presented as a "strawman" for the delegates to debate. Discussion then began along the following lines:

- **Road-map Content:** In small groups, delegates were asked to discuss the "strawman" and add their own thoughts to the ideas already put forward.

This included any missing elements or identification of any unnecessary elements.

- **Prioritisation:** The group was then asked to plot out their critical pathways through the road-map, examining the correct ordering of items on the road map.
- **Categorisation:** The next task was to examine the specific categorisation of road-map items into the technology, commercial and political pathways.
- A free-ranging plenary discussion where their future vision of automated compliance checking was discussed and the attendees could raise any further points.
- Initial validation of the draft road-map. Where the results of the day were re-presented to participants to identify any immediate issues.

Based on the consultation event the final road-map was produced. This consisted of an ordered, prioritised list of tasks, with each task based on a previously elicited obstacle. There were additions and some removal of items. One interesting point, is participants viewed that increasing adoption of BIM should not be included on the road-map, due to the fact that automated regulatory compliance should be seen as a driver for increased BIM adoption, not being dependent upon it.

5.1. Roadmap

The final comprehensive road map, considering political, commercial and technological factors, is presented in tabular form in Tables 5, 6 and 7. In these tables the letter T refers to a technical item, P for a political item and C for a commercial item.

The participants prioritised the items following a simpler version of standard product research and development approaches. This describes the stages that development of innovative product/process must go through;

1. Research.

2. Development of pilot or proof of concept.
3. Industrialisation of pilot or proof of concept to commercial standard.
4. Scaling of industrialised product or process to entire sector.

In total there were 11 technical, 6 commercial and 6 political items in the road-map. It is also interesting to note that the balance of items switches from political in early stages to commercial in the later stages, as political obstacles are overcome and commercial concerns take precedence.

5.2. A Vision for the Future of Automated Regulatory Compliance

The vision presents a view on what the future of automated of compliance checking will look like. It proposes the "new" process for automation of compliance checking, that was elicited during our consultation process. This is shown in Figure 2 and its key concepts are drawn from items within our road-map (from Tables 5, 6 and 7).

In this new vision, authors specify the regulations, requirements and standards against which a built environment asset is to be checked against using an authoring tool that creates digitised regulations. This assumes the successful navigation of the challenging process of creating digitisable rules from human readable documents. Drawn from road-map items 1, 2, 5, 12, 17 and 21.

Then, subsequently, an actor within the built environment domain, works using a human aided design package on a virtual model of the physical asset. This design package utilises the compliance checking system to automate aspects of the design and ensure the actor's work meets the regulations, requirements and standards. Drawn from road-map items 7, 11, 12, 15 and 18.

This is then formally checked against these regulations, requirements and standards. To achieve this, the model is submitted to a compliance checking system. This compliance checking system, then (depending on the level of automation being achieved) either: (a) automatically provides a result, or (b) assists an approved regulator to come to a decision, by assessing some elements automatically. Additionally, compliance checking systems can manage the overall checking process and guide approved regulator through the process even if

No	Capability	Category	Description
Stage 1 - Research.			
1	Cataloguing and prioritising regulations that are suitable for automation	T	Determining what regulations can currently be automated is a key prerequisite.
2	Engaging in direct consultation with Ministry of Housing, Communities and Local Government building regulation policy unit and with Building Regulation Advisory Committee	P	Further engage policy makers/implementors in the digitisation agenda
3	Developed green and white papers for presentation to government and establish funding	P	Presentation of the case for digitisation of compliance checking to funding to establish funding to conduct proof of concept prototype
Stage 2 - Development of pilot or proof of concept			
4	Development of rule processes to track decisions, feedback, and uncertainty	T	Development of compliance checking processes that are able to deliver the required traceability, feedback methods to allow for the requirements of checking at various points in the asset life cycle
5	Detailed mapping of digitised regulation/requirement/standards processes	T	Development of process map of the industry considering automated compliance checking. Phased to consider steps toward adoption
6	Digitisation to be given voice with policy-implementors	P	Ensure that digitisation is part of the future plan for built environment regulations
7	Development of an understanding of parallel regulations	P	Understand how other regulations influence the digitisation of regulations/requirements in the built environment

Table 5: Road-map - Stages 1 and 2

No	Capability	Category	Description
Stage 3 - Industrialisation of pilot or proof of concept.			
8	Persistent data linkages between requirements and supplied product to prevent variation on specification	T	Data linkages to prevent use of replacement products within an asset (during construction or in-use) from invalidating compliance with regulations/requirements
9	Chain of custody of materials and data	T	Technologies to support the capturing of chain of custody for materials and their data
10	Accommodate multiple data models and multiple data dictionaries	T	Enable checking tools to support multiple dictionaries and data models
11	Specification of a continual feedback loop process to incorporate appeals/derogations/determinations data in reviewing regulations	T	Defining a process to properly manage reviewing of regulations based on innovations in design
12	Production of audience specific guidance on digitisation of regulations or requirements	C	In order to overcome scepticism and resistance to change guidance will be produced, targeted to specific audiences, to convey the aims/objectives/benefits of digitisation of regulations/requirements. Additionally, will support more complete and consistent BIM usage. This will also grow wider awareness.

13	Detailed evidence-based business model for digitization of regulatory compliance	C	Development of evidence-based business model in order to motivate and showcase benefits of adoption of automated checking. Balancing risk and opportunity. Additionally, this will expose the cost time and resource drains current processes impose.
14	Explore routes to export developed toolchains to international audience and exploit international developments	C	Provides support for the digital compliance services market by increasing international market
15	Creation of standard data and criteria for social, environment and economic impact assessments	P	To reduce the burden of open ended and undefined expectations
16	Conducting Impact assessment of digitisation of regulations	P	

Table 6: Road-map - Stage 3

No	Capability	Category	Description
Stage 4 - Scaling of industrialised product or process.			
17	Investigation of relationship between regulations and identification of overlaps and gaps	T	Utilisation of digitised regulations to perform details analysis of regulatory landscape
18	Enabling development of generative design based on regulations and requirements	T	Development of approaches to automate the design of assets based on regulations/requirements
19	Consistent/Structured data models and APIs (Application Programming Interface) for compliance checking	T	Development/improvement of APIs to allow widespread interface with compliance systems
20	Continuously checking the quality of assets using calibrated instrumentation along with other data sources	T	Provides the ability to determine if physical assets comply with regulations/requirements throughout their life cycle, without the need for extensive human inspection
21	Definition of precise digitised regulation clauses	T	In order to be digitisable regulations must be available for analysis and rewriting so as to reduce the need for interpretation.
22	Calculation method validation services	C	Providing service to enable software tool calculation methodologies (as utilised in checking) to be validated, providing confidence to end-users

23	Develop robust inspection methods/rules to reduce dependence on human inspectors	C	Processes/methods/rules to allow/support implementation of new technology
24	Professional development and training in compliance checking for all that interface with it – including clients and supply chain.	C	Development of training materials and delivery mechanisms for the entire industry (all stakeholders)

Table 7: Road-map - Stage 4

not all decision making cannot be automated. This process should incorporate multiple sources of data and allow for the provision of any needed additional processes i.e. appeals. Drawn from road-map items 4, 9, 10, 11, 19 and 22.

The final element of this vision is the ability to automatically check, based on data collected (e.g. from sensors) the physical asset (once constructed) against regulations or requirements. Drawn from road-map items 20 and 23.

Thus, the following key changes between this vision and current regulatory compliance approaches are:

- Regulations requirements and standards are stored in a digitised form from which human readable documents can be generated.
- Compliance checking systems can aid (or even remove the need for) approved regulator in making decisions by performing elements of the compliance checking automatically.
- Compliance checking systems aid approved regulator by managing the overall checking process (e.g. recording results, ensuring complete coverage of regulations) even if all decision making cannot be automated.
- Compliance checking systems also have the ability to check the physical asset (if it exists) against the regulations in addition to the virtual model.

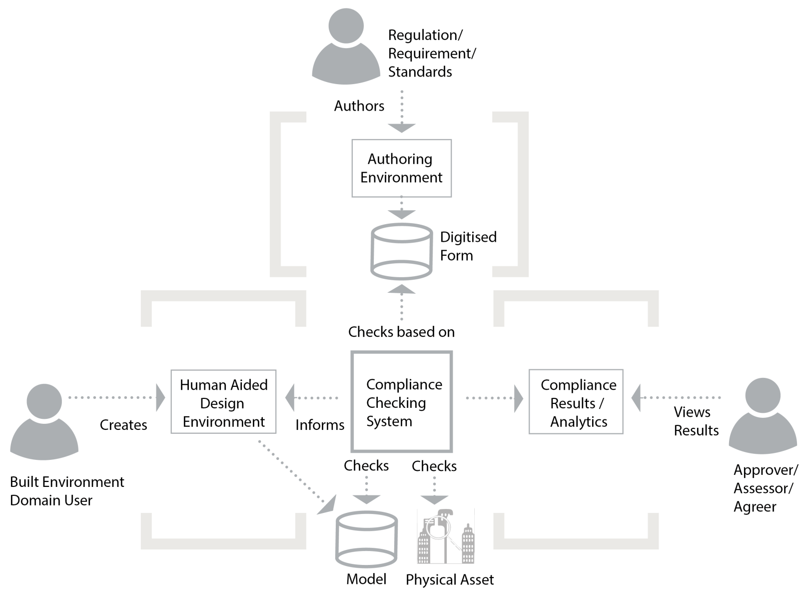

Figure 2: A Vision for Automated Regulatory Compliance

6. Roadmap Validation

In order to validate the road-map, a series of interviews were conducted with 6 industry experts (who did not attend the consultation). These 6 experts were drawn from the domains of; (a) building services, (b) BIM experts, (c) digital transformation, (d) architectural design, and (e) environmental experts.

The purpose of these interviews was to verify the findings and introduce small modifications to the results of the consultation.

At the conclusion of the interviews the final road map was deemed by participants to be ambitious but achievable given sufficient government support and funding. In particular one leading industry figure who was interviewed commented publicly:

" ... their initial findings have shown the need for this work to happen and indeed the positive response to compliance checking shifting from a manual endeavour to one that is supported by computer driven automation allowing a

swifter and more integrated process. I would encourage you to take time to read this report and consider the need for the road map, further research and ultimately the policy recommendations to be made. There is a mutualism between compliance checking and digital workflows and now is the time to make it happen."

Overall the following key pieces of feedback were gathered to guide future work in this area:

- Any automated checking system should aim at producing guidance rather than totally autonomous compliance.
- There is already some interest in this area forming in the UK Government.
- There is a view that automation may be more practical in conventional projects rather than in multiuse-use, complex geometry projects.
- Automated regulatory compliance checking requires government commitment and stewardship to succeed.
- An alternative to the construction industry developing its own approach is the risk of external disruption from outside of the industry.

7. Conclusion

The digitisation of compliance checking is critical to the delivery of a safer and more efficient digital built environment. Failure to comply can have catastrophic effects and current manual based checking processes are timely, costly and have room for error.

This paper has sought to explore how these challenges can be addressed through automated checking, which brings the required time, cost and quality improvements. To achieve this it has aimed to ascertaining the blockers/obstacles that are preventing the widespread adoption of the digitisation of regulatory compliance in the built environment and formulating a road map together with industry traction to drive forward adoption of digitised checking processes across both academic and industrial contexts.While the consultation was conducted in the UK, the limitations identified are general, and thus, the road-map can be applied to any developed country.

The key output of the work is a road map offering a comprehensive and methodical list of next steps. This is a plan for the next several years that brings the construction industry to the verge of mass industrialisation of automated compliance checking.

This road-map is organised into four phases and follows a staged approach including a phase of research, a pilot or proof of concept, a phase of industrialisation, where technologies developed for the pilot are matured and finally, commercial adoption. More specifically each of these stages includes: :

- **Research and Stakeholder engagement:** catalogue and prioritise regulations with the view of digitising for rule development.
- **Piloting:** develop rules alongside a common language and demonstrate working to identify areas for improvement.
- **Industrialisation:** build a product or process to meet majority of needs, trial and test in representative environment and capture key metrics, refine and ready for scaling.
- **Scaling:** develop audience specific training and guidance, establish methods for user feedback and continually refine alongside pathways for enhancement.

In addition to developing the road map, this paper also measured industry attitudes to the adoption of automated compliance checking through a survey. The results were overwhelmingly positive, with the vast majority of respondents believing that adoption of automation was both feasible and desirable. There were caveats and suggestions, the primary on being that automation should have human oversight. It is envisioned that this oversight will consist of a qualified human performing some checks that could not be fully automated, but also having the ability to interrogate and override, if appropriate, automated decisions.

Thus, this paper's findings present a positive response to transforming the built environment's existing compliance system. They give confidence that the industry can achieve a significant level of automation checking and expressed the importance of considering political, commercial and technological factors along the journey. This included the need for a degree of human oversight until the right level of trust is established in automation.

Specifically this paper sought to answer two research questions:

1. **Why has automated regulatory compliance not yet achieved widespread adoption in the built environment domain?**: To answer this question, this study has firstly identified that the attitudes within the construction industry are largely in favour of the development of automated regulatory compliance. However, there are still obstacles that must be overcome. This work has elicited these obstacles (presented in Section 4) from literature and industry consultation. These obstacles are not just technical in nature, but also commercial and political. More importantly, our industry consultation identified that commercial and political issues were, in fact, currently viewed as more significant than technical obstacles.
2. **What is a viable route towards adoption for automated regulatory compliance?**: This question has been answered by the production of our road-map (Section5) that documents a comprehensive validated set of steps that can, over next several years, achieve a transformation of the regulatory compliance system, bringing the construction industry to the verge of mass adoption of automated compliance checking.

It is our view that the adoption of automated compliance checking has, even considering continued human oversight, the potential to greatly improve productivity in construction. Enabling human assessors to check more regulations in a given time. Additionally, this will grant designers the ability to pre-check their work, leading to a reduction in errors. More specifically, the following impacts on productivity are envisioned: (a) increased compliance certainty, (b) enhanced accuracy and accountability and (c) accelerated reporting. In the future our road-map will form one element of the wider "Digital Built Britain" agenda where it will be widely released and consensus built around its contents.

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References

[1] N. O. Nawari, Building Information Modeling:Automated Code Checking and Compliance Processes, Taylor and Francis, 2018. doi:10.1201/9781351200998.

[2] T. H. Beach, Y. Rezgui, H. Li, T. Kasim, A rule-based semantic approach for automated regulatory compliance in the construction sector, Expert Systems with Applications 42 (12) (2015) pp. 5219–5231. doi:10.1016/j.eswa.2015.02.029.

[3] B.-H. Goh, E-government for construction: The case of singapore's corenet project, in: Research and Practical Issues of Enterprise Information Systems II, Springer US, Boston, MA, 2008, pp. 327–336. doi:10.1007/978-0-387-75902-9_34.

[4] British Standards Institution, PAS 1192-3: 2014-Specification for information management for the operational phase of assets using building information modelling (2014) [cited 3-August-2019].
URL https://shop.bsigroup.com/ProductDetail?pid=000000000030311237

[5] S. Azhar, Building information modeling (BIM): Trends, benefits, risks, and challenges for the aec industry, Leadership and Management in Engineering 11 (3) (2011) pp. 241–252. doi:10.1061/(ASCE)LM.1943-5630.0000127.

[6] C. Eastman, J. min Lee, J. kook, Y. suk Jeong, J. kook Lee, Automatic rule-based checking of building designs, Automation in Construction 18 (8) (2009) pp. 1011–1033. doi:10.1016/j.autcon.2009.07.002.

[7] D. Greenwood, S. Lockley, S. Malsane, J. Matthews, Automated compliance checking using building information models, in: The Construction, Building and Real Estate Research Conference of the Royal Institution of Chartered Surveyors, 2010, pp. 266–274 [cited 25-July-2019].
URL https://core.ac.uk/download/pdf/5901165.pdf

[8] P. X. Zou, X. Xu, J. Sanjayan, J. Wang, Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives, Energy and Buildings 178 (2018) pp. 165 – 181. doi:https://doi.org/10.1016/j.enbuild.2018.08.040.

[9] Dame Judith Hackitt, Independent Review of Building Regulations and Fire Safety: final report (2018) [cited 10-August-2019].
URL https://www.gov.uk/government/publications/independent-review-of-building-regulations-and-fire-safety-final-report/

[10] J. Dimyadi, R. Amor, Computer-assisted Regulatory Compliance Checking, in: 12th New Zealand Computer Science Research Student Conference (NZCSRSC), 2013 [cited 15-February-2020].
URL https://www.cs.auckland.ac.nz/~trebor/papers/DIMY13B.pdf

[11] J. Dimyadi, R. Amor, Automated Building Code Compliance Checking – Where is it at?, Proceedings of the 19th World Building Congress: Construction and Society, 5-9 May (2013) pp. 172–185doi:10.13140/2.1.4920.4161.

[12] E. Hjelseth, BIM-Based Model Checking (BMC), American Society of Civil Engineers, 2015, pp. 33–61. doi:10.1061/9780784413982.ch02.

[13] T. Krijnen, Methodologies for requirement checking on building models, Proceedings of the 13th International Conference on Design and Decision Support Systems in Architecture and Urban Planning, June 27-28, 2016 [cited 15-February-2020].
URL https://research.tue.nl/en/publications/methodologies-for-requirement-checking-on-building-models-a-techn

[14] Sarker, Suprateek, A. S. Lee, Using A Positivist Case Research Methodology To Test Three Competing Theories-In-Use Of Business Process Redesign, Journal of the Association for Information Systems 2 (7) (2002) pp. 277–303. doi:10.17705/1jais.00019.

[15] S. J. Fenves, Tabular decision logic for structural design, Journal of the Structural Division 92 (6) (1966) pp. 473–490 [cited 15-February-2020].
URL https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0014476

[16] C. S. Han, J. C. Kunz, K. H. Law, Making Automated Building Code Checking A Reality, Facility Management Journal (1997) pp. 22–28 [cited 15-February-2020].
URL https://www.semanticscholar.org/paper/Making-Automated-Building-Code-Checking-A-Reality-Han-Kunz/cba1094ab4087c7815c6999ea4995f965f4a086b

[17] L. Ding, R. Drogemuller, M. Rosenman, D. Marchant, Automating code checking for building designs - DesignCheck, in: Clients Driving Innovation: Moving Ideas into Practice, Cooperative Research Centre (CRC) for Construction Innovation, 2006, pp. 1–16 [cited 20-August-2020].
URL http://ro.uow.edu.au/engpapers/4842/

[18] X. Tan, A. Hammad, P. Fazio, Automated Code Compliance Checking

for Building Envelope Design, Journal of Computing in Civil Engineering 24 (2) (2010) pp. 203–211. doi:10.1061/(ASCE)0887-3801(2010)24:2(203).

[19] D. M. Salama, N. M. El-Gohary, Semantic Modeling for Automated Compliance Checking, in: Computing in Civil Engineering (2011), American Society of Civil Engineers, Reston, VA, 2011, pp. 641–648. doi:10.1061/41182(416)79.

[20] S. Zhang, J.-k. Lee, M. Venugopal, J. Teizer, C. Eastman, Integrating BIM and Safety: An Automated Rule-Based Checking System for Safety Planning and Simulation, Proceedings of CIB W99 Conference (2011) pp. 1–13 [cited 20-Feburary-2020].
URL https://pdfs.semanticscholar.org/7562/8a5f770262413dd86380b6e4128a0beae761.pdf

[21] E. Hjelseth, Experiences on converting interpretative regulations into computable rules, in: Proceedings of the 29th International Conference of CIB W78, Beirut, Lebanon, ITC Digital Library, 2012, pp. 4–13 [cited 10-February-2020].
URL https://www.jus.uio.no/ifp/om/organisasjon/seri/arrangementer/hjelseth_tks-2013_cib_lebanon-2012_cairo-2010.pdf

[22] J. Melzner, S. Zhang, J. Teizer, H.-J. J. Bargstädt, A case study on automated safety compliance checking to assist fall protection design and planning in building information models, Construction Management and Economics 31 (6) (2013) pp. 661–674. doi:10.1080/01446193.2013.780662.

[23] J. a. P. Martins, A. Monteiro, LicA: A BIM based automated code-checking application for water distribution systems, Automation in Construction 29 (23) (2013) pp. 12–23. doi:10.1016/j.autcon.2012.08.008.

[24] D. M. Salama, N. M. El-Gohary, Semantic text classification for supporting

automated compliance checking in construction, Journal of Computing in Civil Engineering 30 (1). doi:10.1061/(ASCE)CP.1943-5487.0000301.

[25] J. C. P. Cheng, M. Das, A BIM-based web service framework for green building energy simulation and code checking, Journal of Information Technology in Construction 19 (19) (2014) pp. 150–168 [cited 10-February-2020]. URL https://www.itcon.org/paper/2014/8

[26] Y. C. Lee, C. M. Eastman, J. K. Lee, Automated Rule-Based Checking for the Validation of Accessibility and Visibility of a Building Information Model, in: Computing in Civil Engineering 2015, American Society of Civil Engineers, Reston, VA, 2015, pp. 572–579. doi:10.1061/9780784479247.071.

[27] J. K. Lee, Building Environment Rule and Analysis (BERA) Language and its Application for Evaluating Building Circulation and Spatial Program, Ph.D. thesis, Georgia Tech (2011) [cited 1-August-2019]. URL https://smartech.gatech.edu/handle/1853/39482

[28] A. L. C. Ciribini, M. Bolpagni, E. Oliveri, An Innovative Approach to e-public Tendering Based on Model Checking, Procedia Economics and Finance 21 (2015) pp. 32–39. doi:10.1016/S2212-5671(15)00147-1.

[29] S. Macit, G. Suter, A Hybrid Model for Building Code Representation Based on Four-Level and Semantic Modeling Approaches, CIB W78 Conference (2015) pp. 517–526 [cited 2-Februray-2020]. URL https://www.semanticscholar.org/paper/A-Hybrid-Model-for-Building-Code-Representation-on-Macit-Ilal/275b0ffac95be687faec31615e15ec32162c80f2

[30] J. Zhang, N. M. El-Gohary, Automated information transformation for automated regulatory compliance checking in construction, Journal of Computing in Civil Engineering 29 (4). doi:10.1061/(ASCE)CP.1943-5487.0000427.

[31] N. Nisbet, J. Wix, D. Conover, The Future of Virtual Construction and Regulation Checking, John Wiley & Sons, Ltd, 2009, Ch. 17, pp. 241–250. doi:10.1002/9781444302349.ch17.

[32] S. Zhang, J. Teizer, J. K. Lee, C. M. Eastman, M. Venugopal, Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules, Automation in Construction 29 (2013) pp. 183–195. doi:10.1016/j.autcon.2012.05.006.

[33] J. Zhang, N. M. El-Gohary, Semantic NLP-Based Information Extraction from Construction Regulatory Documents for Automated Compliance Checking, Journal of Computing in Civil Engineering 30 (2). doi:10.1061/(ASCE)CP.1943-5487.0000346.

[34] J. Zhang, N. M. El-Gohary, Extending Building Information Models Semiautomatically Using Semantic Natural Language Processing Techniques, Journal of Computing in Civil Engineering 30 (5). doi:10.1061/(ASCE)CP.1943-5487.0000536.

[35] S. Hakim, F. Re Cecconi, M. C. Dejaco, S. Maltese, Rules complexity classification for automated compliance checking, in: Digital Proceedings of the 24th European Group for Intelligent Computing in Engineering International Workshop on Intelligent Computing in Engineering 2017, 2017, pp. 136–145 [cited 2-February-2020].
URL https://www.nottingham.ac.uk/conference/fac-eng/eg-ice2017/documents/papers/40-abstract.pdf

[36] J. Dimyadi, P. Pauwels, R. Amor, Modelling and accessing regulatory knowledge for computer-assisted compliance audit, Journal of Information Technology in Construction 21 (21) (2016) pp. 317–336 [cited 10-Februray-2020].
URL https://www.itcon.org/paper/2016/21

[37] B. Zhong, C. Gan, H. Luo, X. Xing, Ontology-based framework for building environmental monitoring and compliance checking under BIM en-

vironment, Building and Environment 141 (2018) pp. 127–142. doi:10.1016/j.buildenv.2018.05.046.

[38] S. Jiang, N. Wang, J. Wu, Combining BIM and Ontology to Facilitate Intelligent Green Building Evaluation, Journal of Computing in Civil Engineering 32 (5). doi:10.1061/(ASCE)CP.1943-5487.0000786.

[39] R. Zhang, N. M. El-Gohary, A clustering approach for analyzing the computability of building code requirements, in: Construction Research Congress 2018, pp. 86–95. doi:10.1061/9780784481264.009.

[40] N. O. Nawari, A Generalized Adaptive Framework (GAF) for Automating Code Compliance Checking, Buildings 9 (4) (2019) pp. 86. doi:10.3390/buildings9040086.

[41] N. O. Nawari, A Generalized Adaptive Framework for Automating Design Review Process: Technical Principles, Advances in Informatics and Computing in Civil and Construction Engineering (October) (2019) pp. 405–414. doi:10.1007/978-3-030-00220-6_48.

[42] N. Bus, F. Muhammad, B. Fies, Semantic topological querying for compliance checking, in: eWork and eBusiness in Architecture, Engineering and Construction, no. European Conference on Product and Process Modelling 2018, CRC Press, 2018, pp. 459–464. doi:10.1201/9780429506215-57.

[43] C. Zhang, Requirement checking in the building industry : enabling modularized and extensible requirement checking systems based on semantic web technologies, Ph.D. thesis, Department of the Built Environment (2019) [cited 19-Februray-2020].
URL https://research.tue.nl/en/publications/requirement-checking-in-the-building-industry-enabling-modularize

[44] N. O. Nawari, Generalized adaptive framework for computerizing the building design review process, Journal of Architectural Engineering 26 (1). doi:10.1061/(ASCE)AE.1943-5568.0000382.

[45] M. Messaoudi, N. O. Nawari, R. Srinivasan, Virtual building permitting framework for the state of florida: Data collection and analysis, in: Computing in Civil Engineering 2019, pp. 328–335. doi:10.1061/9780784482421.042.

[46] M. Messaoudi, N. O. Nawari, BIM-based Virtual Permitting Framework (VPF) for post-disaster recovery and rebuilding in the state of Florida, International Journal of Disaster Risk Reduction 42 (2020) pp. 101349. doi:https://doi.org/10.1016/j.ijdrr.2019.101349.

[47] J. Dimyadi, W. Solihin, E. Hjelseth, Classification of BIM-based Model checking concepts, Journal of Information Technology in Construction 21 (2016) pp. 354–370 [cited 10-February-2020].
URL https://www.itcon.org/paper/2016/23

[48] U. Gurevich, R. Sacks, Longitudinal study of bim adoption by public construction clients, Journal of Management in Engineering 36 (4) (2020) pp. 05020008. doi:10.1061/(ASCE)ME.1943-5479.0000797.